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A Sensitivity-Based Gate Location Algorithm for Optimal Mold Filling During the Resin-Transfer Molding (RTM) Process

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Abstract

A sensitivity-based gate location algorithm for optimal filling of molds in the resin-transfer molding (RTM) process is described in this report. In the RTM process for composite manufacturing, a fiber preform is placed inside a mold and resin is injected into it under high pressures through inlets or gates. Finite-element-based resin-flow simulation codes have been successfully used for modeling and analysis of the process. This process is increasingly used for the manufacture of three-dimensional (3-D) composite parts with material and geometric complexities. In such cases, the locations of the gates cannot be determined easily except by expensive trial and error, both experimentally and computationally. Hence, systematic search methods working in tandem with flow simulations are necessary to determine gate locations for optimal filling. In this report, the governing equation for pressure along with the boundary conditions is differentiated with respect to the coordinates of each gate. The resulting system of pressure sensitivity fields is solved in parallel with the flow problem. The sensitivity fields are used to compute the gradients of the fill time with respect to the gate's coordinates. A standard gradient-based optimization algorithm is then used to determine the new coordinates of the gate location. This methodology of finding optimal gate locations for mold filling in RTM was demonstrated with a case study in which mold-filling time was minimized for the case of a single gate.

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1. Introduction

Liquid-injection molding processes, such as resin-transfer molding (RTM), are being used in the manufacture of composite structures that have varying material properties in aerospace and defense applications. These processes are attractive because they enable the manufacture of parts with good strength-to-weight ratio and with material properties tailored to specifications and in desired "net" shapes. In RTM, the reinforcement material or "preform" is placed inside a mold. The mold is closed and the resin is injected into it at high pressure through inlet ports or "gates." Outlet ports or "vents" are used to enable the displaced air to escape out of the mold. The resin impregnates the preform and polymerizes to form the solid part, which is then demolded [1]. Optimization of the filling process is critical due to the need to decrease the process cycle time and to complete the filling before the resin starts to cure.

Finite-element-based mold-filling simulations based on process models can track the flow front location during the impregnation of the preform, once the user has specified the locations of inlet gates and vents. However, there are as many choices for gate and vent locations as there are nodes in the finite-element mesh for the mold geometry. For parts having material and geometric complexities, the location of gates is nonintuitive, and extensive trial and error is involved in optimizing their position. Hence, there is a need for a systematic search method which can be interactively coupled with filling-simulation capabilities to determine optimally placed gates and vents in order to minimize fill times as well as dry spot formation.

In earlier work [2, 3], analytical sensitivity-based techniques have been developed that embed the process models in a gradient-based optimization framework to develop a powerful tool for optimal mold design for polymer processes such as injection molding, extrusion, and compression molding. In sensitivity-based optimization algorithms, the governing equations and boundary conditions, including a process model, are differentiated with respect to each design parameter to yield a system of equations for the sensitivity of the primary process variables (such as pressure and velocity) with respect to that design parameter. The new systems of governing equations in the design sensitivities are then solved to yield the design sensitivity fields. These design sensitivity fields can then be used to evaluate the gradients of the cost function, which measures the efficacy of the design under consideration. These gradients can then be used in a standard gradient-based optimization algorithm to improve the design. In the case of molding processes such as RTM, the problem involves a moving boundary, hence a domain, that changes at every time-step, thus adding to the challenge in computing design sensitivity fields.

In this report, a design sensitivity-based optimization algorithm is presented for the RTM process with the injection of resin at constant pressure. The process model is presented and the numerical solution technique is described. The solution method is implicit in time, thus making the computation of the design sensitivity fields challenging. The governing equations for the design sensitivity fields are derived, which are directly parallel to those of the primary problem and can be solved in the same manner. The gradients of the cost function (i.e., fill time) were derived in terms of the design sensitivity fields. The results of a case study in fill time minimization are then presented.

2. RTM: Process Modeling and Liquid-Injection Molding Simulations

The flow of resin through porous media, such as fiber preforms during the RTM process, is governed by Darcy's Law [4]:

$$\mathbf{u} = \frac{-\mathbf{K}}{\mu} \bullet \nabla \mathrm{P}. \tag{1}$$

Here, $\mathbf{u}$ is the Darcy's velocity, which is defined as the total flow rate per total cross-sectional area; K is the permeability tensor, which characterizes the ease of flow through the fiber preform; and μ is the viscosity of the resin. This, when coupled with the continuity equation for incompressible flow, this gives the governing equation for the fluid pressure field inside a region permeated by the fluid:

$$\nabla \bullet \left(\frac{\mathbf{K}}{\mu} \bullet \nabla \mathrm{P}\right) = 0. \tag{2}$$

The boundary conditions for a constant pressure injection are:

$$\begin{aligned} &P(\vec{x}_{gate}) = P_0, \\ &P(\vec{x}_{flowfront}) = 0 \quad \textit{at free surface}, \text{ and} \\ &\vec{n} \bullet \left(\frac{K}{\mu} \bullet \nabla P\right) = 0 \quad \textit{at mold wall.} \end{aligned} \tag{3}$$

3. Gate Location: Derivation of Pressure Sensitivity Fields

Consider a single gate location for a given two-dimensional mold that has the coordinates (ε,η). The pressure fields at each time-step and the fill time are dependent on the location of this gate and the pressure imposed at it. The effect of the gate location on the pressure field is encapsulated in the design sensitivity fields, $\frac{\partial P}{\partial \varepsilon}$ and $\frac{\partial P}{\partial \eta}$. The equations governing these fields can be derived directly from the primary partial differential equation (PDE), describing the resin flow in the mold by direct differentiation as follows:

$$\begin{aligned} &\frac{\partial}{\partial \varepsilon}\left(\nabla \bullet (\frac{\mathbf{K}}{\mu} \bullet \nabla \mathrm{P}) = 0\right) && \text{and} && \frac{\partial}{\partial \eta}\left(\nabla \bullet (\frac{\mathbf{K}}{\mu} \bullet \nabla \mathrm{P}) = 0\right) \\ &\Rightarrow \nabla \bullet (\frac{\mathbf{K}}{\mu} \bullet \nabla \frac{\partial P}{\partial \varepsilon}) = 0 && && \Rightarrow \nabla \bullet (\frac{\mathbf{K}}{\mu} \bullet \nabla \frac{\partial P}{\partial \eta}) = 0. \end{aligned} \tag{4}$$

Thus, we obtain auxiliary PDEs for the design sensitivity fields. The boundary conditions for these PDEs are similarly derived from the original boundary conditions and are stated as follows:

$$\begin{aligned} &\frac{\partial P}{\partial \varepsilon}(\vec{x}_{gate}) = -\frac{\partial P}{\partial x} && && \frac{\partial P}{\partial \eta}(\vec{x}_{gate}) = -\frac{\partial P}{\partial y} \\ &\frac{\partial P}{\partial \varepsilon}(\vec{x}_{flowfront}) = 0 \quad \textit{at free surface} && \text{and} && \frac{\partial P}{\partial \eta}(\vec{x}_{flowfront}) = 0 \quad \textit{at free surface} \\ &\vec{n} \bullet (\frac{K}{\mu} \bullet \nabla \frac{\partial P}{\partial \varepsilon}) = 0 \quad \textit{at mold wall} && && \vec{n} \bullet (\frac{K}{\mu} \bullet \nabla \frac{\partial P}{\partial \eta}) = 0 \quad \textit{at mold wall.} \end{aligned} \tag{5}$$

This system of auxiliary equations can now be solved in the same way as the primary problem to yield a solution for the design sensitivity fields at each time step. This approach can be easily extended to multiple gates.

4. Design Sensitivity Analysis for Fill-Time Optimization

In design optimization, the performance of the design is evaluated mathematically using a cost function or response functional. Once evaluated, the gradient of the cost function with respect to the design parameters can be incorporated into any standard gradient-based optimization algorithm to search for the best possible design to minimize the cost function. In gate location optimization, one measure of the performance of the gate(s) is the time it takes to fill the mold. The design sensitivity fields, once determined at each time-step, can be used to find the gradient of fill time with respect to the gate locations. Supposing the volume of the mold is V, for a single gate it can be stated that:

$$V = \int_0^{t_f} Q_{gate}\, dt. \tag{6}$$

Because the volume of the mold is a constant, it follows that:

$$\frac{\partial V}{\partial \varepsilon} = \frac{\partial}{\partial \varepsilon} \int_0^{t_f} Q_{gate}\, dt = 0 \text{ and } \frac{\partial V}{\partial \eta} = \frac{\partial}{\partial \eta} \int_0^{t_f} Q_{gate}\, dt = 0. \tag{7}$$

Differentiating the integrals and separating out the terms we get:

$$\int_0^{t_f} \frac{\partial Q_{gate}}{\partial \varepsilon}\, dt + \frac{\partial t_f}{\partial \varepsilon} \quad Q_{gate}(t_f) = 0 \quad and \quad \int_0^{t_f} \frac{\partial Q_{gate}}{\partial \eta}\, dt + \frac{\partial t_f}{\partial \eta} \quad Q_{gate}(t_f) = 0; \tag{8}$$

$$\Rightarrow \quad \frac{\partial t_f}{\partial \varepsilon} = -\frac{\int_0^{t_f} \frac{\partial Q_{gate}}{\partial \varepsilon}\, dt}{Q_{gate}(t_f)} \quad and \quad \frac{\partial t_f}{\partial \eta} = -\frac{\int_0^{t_f} \frac{\partial Q_{gate}}{\partial \eta}\, dt}{Q_{gate}(t_f)}. \tag{9}$$

Case Study: Fill-Time Optimization of a Complex Composite Part

In earlier sections, a sensitivity-based method to determine the gradients of mold fill time with respect to the coordinates of the gates has been derived from the physics of the mold-filling process. This method was coupled with Cauchy's method for unconstrained optimization [5] to obtain a gate location optimization algorithm for RTM. In a case study, the gate location problem was solved for the mold filling of a complex composite part.

The optimization problem is to find the gate location that minimizes fill time for the selected mold geometry and material parameters (Figure 1). The composite part has thicker sections at the center corresponding to the wheel wells. The permeabilities of the preform material are $K_{11}=K_{22}=10^{-9}m^2$ for the thin section and three orders of magnitude lower, $K_{11}=K_{22}=10^{-12}m^2$, for the thick section. The injection at the gate is performed under constant pressure, which was arbitrarily chosen to be 2 atm at the gate. In addition, racetracking channels are created when there is a gap between the preform and the mold wall. The channels provide a path of least resistance to the flow and dramatically affect the flow front movement of the resin in the mold. Thus, the optimal location of the gate to minimize fill time will change.

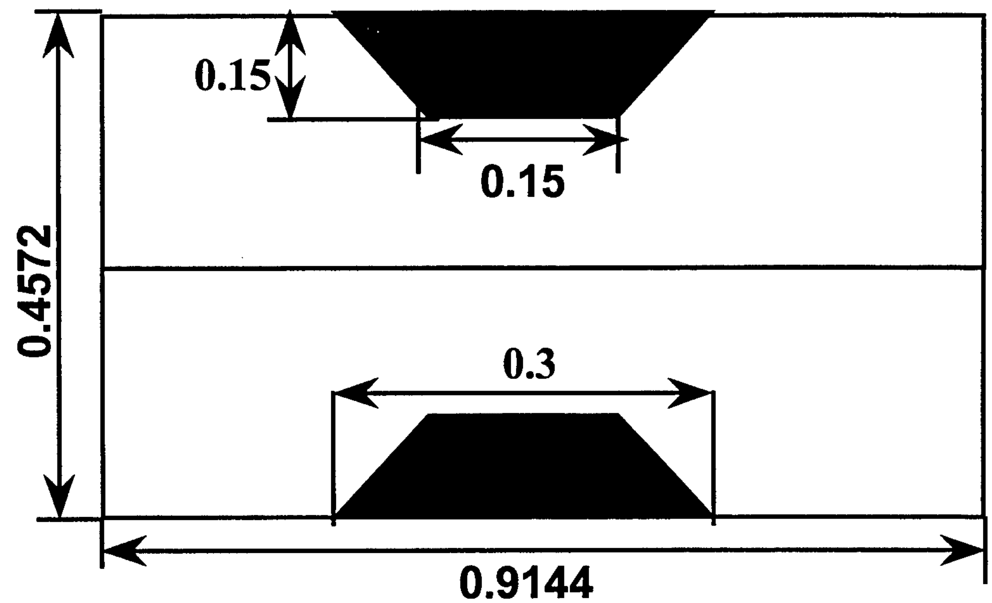

Figure 1. Composite part used for fill-time optimization (units in meters).

The mold geometry was discretized using the PATRAN finite-element preprocessor, and a racetracking channel of 2.54-cm width and 0.64-cm depth around the boundary of the mold was incorporated into the FEM model of the mold. The Laboratory Information Management System (LIMS) [6] was used for simulation of the filling process and for the calculation of the design sensitivity fields. The LIMS software distribution includes LBASIC, a scripting language that can be used both as an interface for the mold-filling simulations and as a computer language. Using these capabilities to seamlessly integrate numerical optimization with mold-filling simulations (Figure 2), the sensitivity-based gate location algorithm was thus coded into a LBASIC script. The optimization study was undertaken for three cases: (1) a part without racetracking and thick sections, (2) a part without racetracking and with thick sections, and (3) a part with both racetracking and thick sections present.

The results from the sensitivity-based gate location algorithm for fill-time optimization are plotted in Figures 3 and 4. As seen in the figures, the algorithm was able to reduce the fill time for each case to a minimum value for every starting point. In addition, it can be seen from the plots of the sequence of the gates generated by the optimization algorithm that it was able to reach the best possible solution in each case. In the cases without racetracking (cases [a] and [b]), the best gate location is at the center of the composite part, whereas in the case with racetracking, the best gate locations lie along the shortest segments of the racetracking channel.

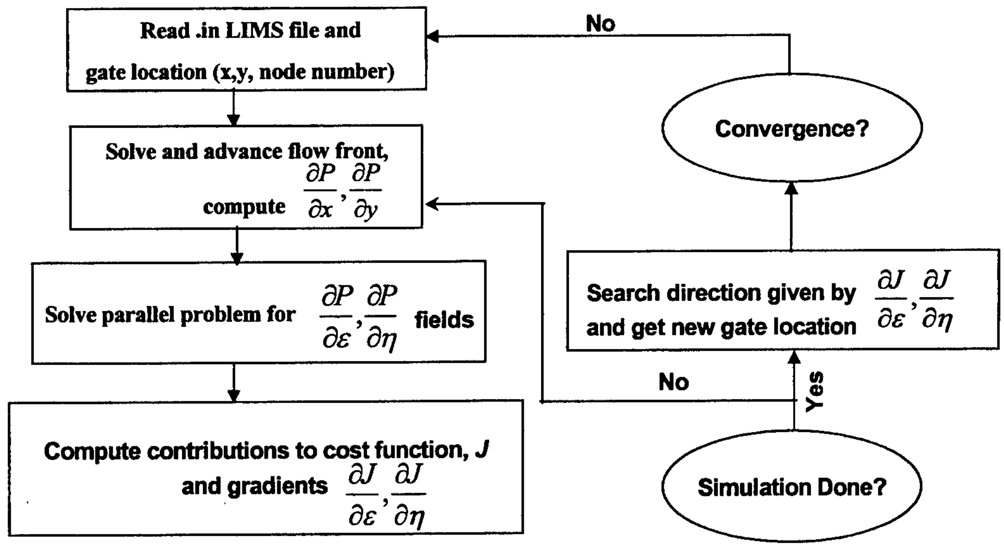

Figure 2. Schematic of sensitivity-based gate location optimization algorithm.

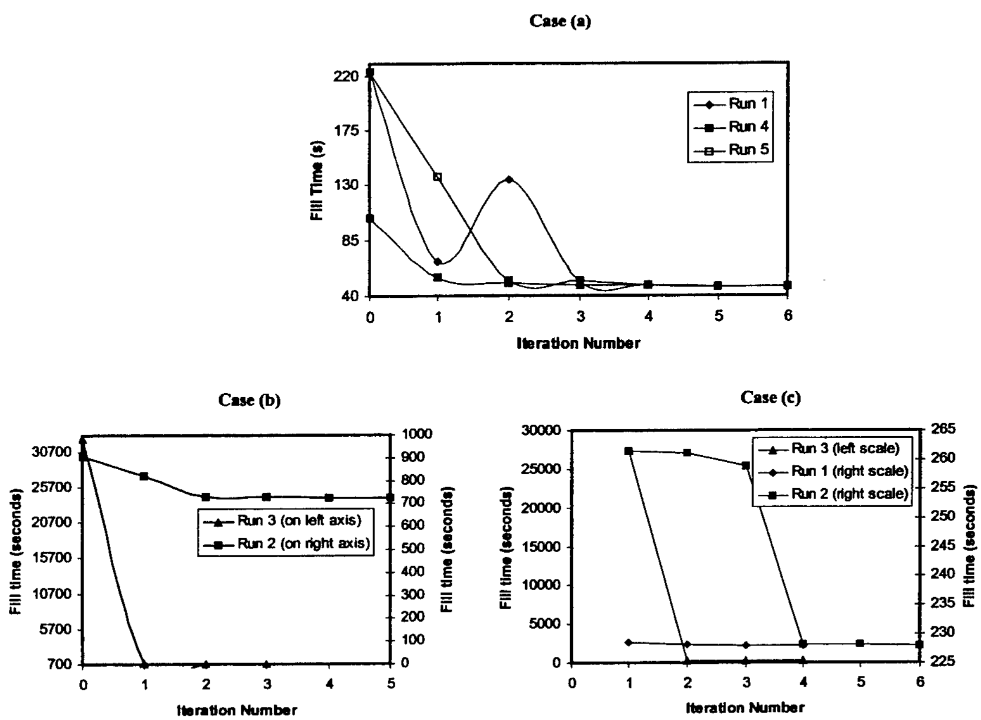

Figure 3. Results from optimization algorithm: plot of fill time with iteration number for part (a) without racetracking and thick sections, (b) without racetracking and with thick sections, and (c) with both racetracking and thick sections present.

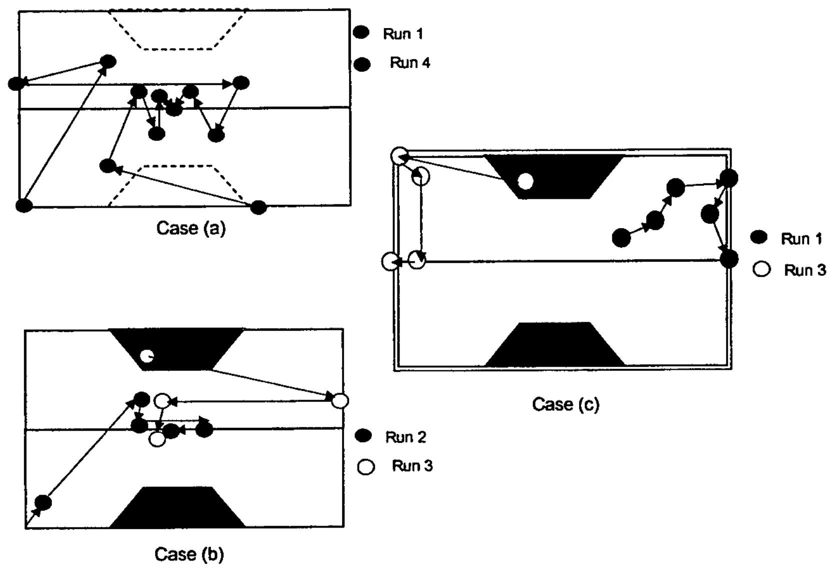

Figure 4. Results from optimization algorithm: plot of movement of gates for two runs of the gradient-based optimizer for each case. It can be noted that in (a) and (b), the optimal location lies at the center of the mold for nonracetracking cases; and in (c), at the centers of the racetracking channels for the racetracking case.

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